[Continued on next page]

(54) Title: COMPENSATION AND CONTROL OF BOTH FIRST-ORDER AND HIGHER-ORDER POLARIZATION-MODE DISPERSION

(57) Abstract: Techniques and devices for controlling or compensating for both the first-order and high-order PMD effects in an optical signal by processing the signal in a fixed DGD stage and a variable DGD stage in sequence.

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COMPENSATION AND CONTROL OF BOTH FIRST-ORDER AND HIGHER-ORDER POLARIZATION-MODE DISPERSION

[0001]   This application claims the benefit of U.S.

5   Provisional Application No. 60/229,953 filed September 1,

2000.

Background

[0002]   This application relates to compensation for

10   and control of optical dispersion, and more specifically,

to techniques for reducing polarization-mode dispersion

in optical media such as optical fibers used in various

fiber systems including optical wavelength-division

multiplexing (WDM) fiber systems.

15   [0003]   Some optical transmission media, e.g., optical

fibers, may be optically birefringent and hence exhibit

different refractive indices for light with different

polarizations along two orthogonal principal directions.

Therefore, an optical signal, comprising of two

20   components along the two orthogonal principal directions

for each frequency, can be distorted after propagation

through the transmission medium because the two

components propagate at different group velocities. One

effect of such dispersion-induced distortion is

25   broadening of optical pulses. This polarization-

dependent optical dispersion is generally referred to as

the first-order polarization-mode dispersion ("PMD").
The degree of the first-order PMD may be approximately
characterized by the average differential group delay
("DGD") between two orthogonal principal states of

5   polarization. PMD also exhibits higher order effects and
further complicates the compensation and management of
the PMD in fiber systems.

[0004]   Typical causes for such birefringence in fibers
include, among others, imperfect circular core and

10   unbalanced stress in a fiber along different transverse
directions. Notably, the direction of one axis of
birefringence of the optical fiber may change randomly on
a time scale that varies, e.g., from milliseconds to
hours, depending on the external conditions. Thus, the

15   DGD in an actual PMD fiber is not a fixed value but a
random variable. In many fiber links in communication
systems, the PMD-induced DGD has a Maxwellian probability
density function.

[0005]   Such polarization-mode dispersion is

20   undesirable in part because the pulse broadening can
limit the transmission bit rate, the transmission
bandwidth, and other performance factors of an optical
communication system. In fact, PMD is one of key
limitations to the performance of some high-speed optical

fiber communication systems at or above 10 Gbits/s per

channel due to the fiber birefringence. It is desirable

to control, manage, or compensate such optical dispersion

in fiber systems.

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Summary

[0006]   This disclosure includes techniques for controlling, managing, or compensating both first-order and higher-order PMD in a two-stage PMD control scheme. The first PMD control stage includes a fixed PMD element designed to produce a fixed DGD for controlling second-order and higher-order PMD in the input optical signal. The second PMD control stage includes a variable PMD element designed to produce a variable DGD for controlling the residual first-order PMD in the input signal after being processed by the first stage. An optical element is interconnected between the fixed PMD element and the variable PMD element to rotate the polarization of the output light from the first stage by a desired angle.

Brief Description of the Drawings

[0007]   FIG. 1 shows one embodiment of a two-stage PMD control device.

[0008]   FIGS. 2, 3, and 4 show exemplary implementations of the device in FIG. 1.

[0009]   FIG. 5 shows one exemplary control algorithm for controlling the operation of the device in FIG. 1.

Detailed Description

[0010]   The techniques and devices of this disclosure are in part based on the recognition that both the first order and higher orders of the PMD in a fiber system need

5   be compensated or managed. Many PMD compensators with different fixed DGD elements connected in series usually require complex feedback control loops that operate in connection with one another to simultaneously adjust a large number of control variables (e.g., 10 or more).

10   Such compensators tend to be structurally complex and respond slowly.

[0011]   FIG. 1 shows one embodiment of a two-stage PMD device 100 that can either operate as a PMD controller for controlling and managing the PMD in a fiber link or a

15   PMD compensator for compensating PMD effects of the fiber link. The first stage 110 is designed to produce a fixed amount of DGD in the received optical signal 101 to produce a modified signal 114. This operation is used to control or compensate for the second and higher order PMD

20   effects in the received signal 101. The second stage 120, optically connected to receive the modified signal 114, is designed to produce a variable DGD in the modified signal 114 to control the residual first-order PMD so that the PMD in the output signal 124 is at a

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desired state or substantially canceled. The operation

of the second stage 120 doses not substantially change

the PMD modification produced by the first stage. This

two-stage design can control or compensate for both

5 first-order and higher-order PMD effects and can reduce

the number of control variables to as less as 5 to

simplify the entire device structure and its control.

[0012] The first stage 110 includes a polarization

transformer 111 to control the polarization of the input

10 optical signal 101 and a fixed DGD element 113 to modify

the DGD in the signal 101. The fixed DGD element 113 may

include an optically-birefringent medium such as a

polarization-maintaining fiber or a birefringent crystal

to produce a fixed delay between two principal states of

15 polarization at a given wavelength. This fixed amount of

DGD is selected according to the desired amount of high-

order PMD effects in the received signal 101. The

polarization transformer 111 can be adjusted in response

to a control signal 151 to rotate a polarization of the

20 input signal 111 to produce a polarization-rotated signal

112 whose polarization is aligned with respect to a

selected axis of the two principal axes of the element

113. A polarization controller with two or three degrees

of freedom, for example, may be used as the polarization
transformer 111.

[0013] The second stage 120 includes a variable DGD
element 123 that responds to a control signal 153 to

5   produce a variable DGD on the received signal 122. A
polarization transformer 121 is included in the input of
the element 123 to rotate the polarization of the
modified signal 114 from the first stage 110 to a desired
direction defined by the variable DGD element 123. This

10   second stage 120 modifies the residual first-order PMD in
the signal 114 to either control the residual first-order
PMD in the signal 124 at a desired value or substantially
cancel the residual first-order PMD.

[0014] The polarization of light may be represented by

15   coordinates along two principal polarization axes that
are orthogonal to each other. Hence, at least two
degrees of freedom are needed to completely control the
polarization. The total degrees of freedom of the two
polarization transformers 111 and 121 may be equal to or

20   greater than 4, to completely control the generally-
arbitrary polarization of the input signal 101 received
by the device 100. Because the variable DGD element 123
has a single degree of freedom, the device 100 has

degrees of the freedom not less than 5. The minimum

number of control variables is 5.

[0015]   In principal, the two stages 110 and 120 may

switch their positions to achieve control over the PMD

5   state of the output beam 124 out of the device 100.

However, when the stage 120 processes the input beam 101

first, the polarization of the output beam from the stage

120 may change significantly between 0 and 2π at a high

speed due to the varying DGD produced by the PMD element

10   123. The stage 110, connected in the downstream of the

stage 120 in the switched position, may not be able to

respond to such rapid change in the light polarization

due to the practical limitations of many commercial

polarization controllers that may be used as the element

15   111. Hence, it may be preferred to place the stages 110

and 120 in the sequence as shown in FIG. 1.

[0016]   In operation of the device 100, the

polarization of the input light 101 is first rotated by

the transformer 111 to align with a selected axis of the

20   two principal axes of the fixed DGD element 113. A fixed

DGD is then produced on the polarization-rotated light

112 to generate the signal 114. The polarization

transformer 121 in the stage 120 rotates the polarization

of the signal 114 to be aligned with a selected axis of

the two principal axes of the variable DGD element 123.

Next, the element 123 processes the polarization-rotated

light 122 to produce a desired variable DGD thereon and

generates the output signal 124. In the above operation,

5   the stage 110 produces the fixed DGD on the input light

101. In comparison with the arrangement where the stage

120 is placed in front of the stage 110, this

substantially reduces the amount of change in

polarization of the signal 114 as the input polarization

10 of the light 101 varies. Hence, the polarization

transformer 121 may be implemented by many commercial

polarization rotators or polarization controllers to

follow the polarization change in the light 114.

[0017]   In the device 100 as shown in FIG. 1, the total

15 of 4 degrees of freedom of two polarization transformers

110 and 120 may be arranged in two different allocations.

In one implementation 200 as shown in FIG. 2, the first

polarization transformer 111 may be a polarization

controller 210 with three degrees of freedom and the

20 second polarization transformer 121 may simply be a

polarization rotator with only one degree of freedom.

The polarization controller for the transformer 111 may

include at least three polarization elements optically

connected in series. See, Heismann, "Analysis of a

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Reset-Free Polarization Controller for Fast Automatic Polarization Stabilization in Fiber-optic Transmission Systems," Journal of Lightwave Technology, Vol. 12, No. 4, April 1994. The polarization rotator for the element

5 121 may be implemented by a rotatable birefringent wave plate 220 with a fixed phase retardation between the two principal axes, e.g., a half-wave plate. The single control variable is the rotation of the wave plate 220 around the optic axis of the device 100. The orientation

10 of the wave plate 220 may be continuously adjusted. The rotation may be a physical rotation of the wave plate 220 or a rotation of the principal polarization axes of the wave plate 220 without physical rotation of the plate itself. The latter may be achieved by using certain

15 electro-optic materials (e.g., properly-cut LiNbO₃ crystals) controlled by an external electric field. Alternatively, the polarization rotator may be a birefringent retarder with its principal axes fixed in space. The phase retardation between the two principal

20 axes, however, is adjustable in response to a control signal 152. This adjustable phase retarder may be formed by an electro-optic material which changes its refractive indices in response to a control electric field, a birefringent thermo-optic material engaged to a

temperature control unit which changes the indices with

the temperature, or a pressure-controlled birefringent

material which changes the indices along two principal

axes when physically squeezed (e.g., a PM fiber engaged

5   to a piezo-electric squeezer). In another

implementation, both transformers 111 and 121 may be a

polarization controller with two degrees of freedom. The

control operation for this implementation may be more

complex than the previous implementation.

10   **[0018]**   FIG. 3 shows an exemplary implementation 300 of

. the device 100 in FIG. 1. A reset-free polarization

controller 310 with 3 degrees of freedom is used as the

first polarization transformer 111 in FIG. 1. A PM fiber

320 with a selected length is used to operate as the

15   fixed DGD element 121. The variable DGD element 123

includes two polarizing beam splitters (PBSs) 330 and 334

and two separate optical paths 331 and 332 connected

therebetween. The optical signal 122 input to the

element 123 is split by the first PBS 330 into two

20   orthogonally-polarized beams respectively received by

optical paths 331 and 332. The optical paths 331 and 332

are designed to have an adjustable delay relative to each

other in response to the control signal 153 so that the

delay between two polarizations can be varied. For

example, the optical path 332 may include an adjustable

portion 333 to change its total optical path length

relative to that of the optical path 331. This may be

achieved by either adjusting the physical length of the

5   path 332 or a refractive index of the path 332 or both of

the physical length and the index. As illustrated in

FIG. 3, a retro-reflector is placed in the path 332 to

change the delay by adjusting its position. The second

PBS 334 combines the beams of two polarizations into a

10 single output beam 124.

[0019]   FIGS. 4 shows another exemplary implementation

400 of the device 100 in FIG. 1 by using multiple fixed

DGD elements 410, 420, etc. in a serial configuration to

form the variable DGD element 123. A polarization

15 rotator (e.g., 411) is placed between two adjacent fixed

DGD elements (e.g., 410 and 420) to rotate the

polarization of light out of a fixed DGD element relative

to the principal axes of the next fixed DGD element. The

allowable orientations of each polarization rotator 411

20 may be set at pre-selected discrete values relative to

other rotators so that the total DGD of the element 123

is discrete and can be adjusted to different discrete

values. Hence, the rotators 411 are controlled together

and such control has only one degree of freedom. See,

Sobiski et al., "Fast First-Order PMD Compensation with

Low Insertion Loss for 10Gbit/s System," Electronic

Letters, Vol. 37(1), pp. 46-48.

[0020]   In yet another implementation, the variable DGD

element 123 may also be a nonlinearly-chirped fiber

grating formed of a birefringent fiber. The overall

length of the fiber grating may be controlled to produce

different DGD values. See, U.S. Patent Application No.

09/253,645 by Cai et al. filed on February 19, 1999.

[0021]   Referring back to FIG. 1, a feedback control

mechanism may be implemented in the above and other

configurations of the device 100 in FIG. 1 to control the

operations of the two stages 110 and 120 in order to

produce the desired PMD in the output signal 124. The

small portion of the output signal 124 may be sampled to

produce a feedback signal for controlling the device 100.

In one embodiment as shown in FIG. 1, an optical splitter

130, such as a fiber coupler or a beam splitter, is

placed in the path of the output beam 124 to produce an

output beam 131 and a feedback beam 132. An optical

detector 140 is coupled to receive the feedback beam 132

and convert it into a detector signal 142. A control

unit 150, coupled to the detector 150, processes the

detector signal 142 to produce the control signals 151,

152, and 153 to respectively control the polarization

transformers 111, 121, and the variable DGD element 123

according to the measured PMD in the output signal 124.

[0022]   The PMD in the output signal 124 of the device

5   100 may be measured by the effects of the PMD on the

signal quality. The signal quality of the signal 124 may

be represented by various performance tests. One

commonly-used performance test is the bit error rate test

that measures the bit error rate in the signal 124. The

10 PMD can increase the bit error rate in the signal 124.

Hence, the control unit 150 can control the elements 111,

121, and 123 to reduce the measured bit error rate. This

test, however, requires the knowledge of the data format

of the digital coding in the output signal 124 and the

15 measurement is format specific. Another performance test

is the eye opening of the eye diagram of the signal 124.

One advantage of this test is that it does not depend on

the digital data format of the optical signal and hence

the monitoring can be achieved without any knowledge of

20 the data format in the received signal. Based on this

test, the control unit 150 controls the elements 111,

121, and 123 to increase eye opening of the eye diagram.

Another format-independent performance test uses one or

more polarimeter to measure the polarization state of the

output signal 124 and the associated PMD. The circuits

and devices for a proper performance test may be included

as part of the control unit 150 or a device coupled

between the control unit 150 and the optical detector

5   140.

[0023]   However the signal quality of the signal 124 is

measured, the control unit 150 is designed to use the

measured signal quality to control the elements 111, 121,

and 123 in order to maintain the signal quality at an

10   acceptable level. One technical challenge is to avoid

local optimization to achieve a global optimization and a

short response time in controlling the elements 111, 121,

and 123 by the feedback control. One feature of the

present disclosure is to apply a special control

15   operation in adjusting the elements 111, 121, and 123 in

the above two-stage PMD device 100.

[0024]   FIG. 5 shows a flowchart for one embodiment of

this special control operation. In essence, the

polarization transformers 111 and 121 are dynamically

20   controlled during the entire operation of the device 100

in response to the measured signal quality of the signal

124. The variable DGD element 123, however, is set into

either a dynamic control state or a static state

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depending on whether the measured signal quality is acceptable to the specific application.

[0025]   In operation, when the signal degradation caused by the PMD is below a tolerance threshold level,
5   the variable DGD element 123 in the second stage 120 may be set to a static state in which its settings are fixed to produce a fixed DGD while the polarization transformers 111 and 121 are dynamically adjusted with the input polarization. For example, the signal
10 degradation may be monitored by measuring the opening of the eye diagram of the output signal 124 with the optical detector 140. When the opening of the eye diagram decreases below a threshold opening level, the variable DGD element 123 is activated to operate in a dynamic
15 state in which the settings of the variable DGD element 123 are dynamically adjusted to produce a varying DGD value as a function of time to bring the signal quality back to the acceptable level. At the same time, the transformers 111 and 121 are being dynamically adjusted.
20 This controlling of the variable DGD element 123 between the static and dynamic states during operation has shown to improve the response time of the feedback control and reduce the probability of operating the feedback loop out of its operating range.

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[0026]   Only a few embodiments are disclosed. However,
it is understood that variations and enhancements may be
made without departing from the spirit of and are
intended to be encompassed by the following claims.

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Claims

What is claimed is:

1.   A device, comprising:

a first polarization-mode dispersion (PMD) element having an input terminal to receive an input optical signal and designed to cause a fixed differential group delay (DGD) in said input optical signal to produce a first output optical signal;

an optical element coupled to said first PMD element to receive said first output optical signal operating to rotate polarization of said first output optical signal to produce a second optical output signal; and

a second PMD element coupled to receive said second output optical signal to produce a variable DGD in response to a control signal to produce an optical output signal.

2.   The device as in claim 1, wherein said second PMD element includes a nonlinearly-chirped fiber grating formed of a birefringent fiber material.

3.   The device as in claim 1, wherein said second

PMD element includes a first optical path to receive

light of a first principal polarization of said second

optical output signal, a second optical path to receive

5   light of a second orthogonal principal polarization of

said second optical output signal, and a control portion

that varies an optical delay between said first and said

second optical paths in response to said control signal.

10   4.   The device as in claim 3, wherein said second

PMD element further includes a first polarizing beam

splitter that splits said second output signal into said

first and said second optical paths and a second

polarizing beam splitter that combines said first and

15   second optical paths.

5.   The device as in claim 1, wherein said second

PMD element includes a plurality of fixed DGD elements

and an adjustable polarization rotator optically

20   connected between two adjacent fixed DGD elements.

6.   The device as in claim 5, wherein said fixed

DGD elements and each adjustable polarization rotator are

configured to produce discrete DGD values.

7.   The device as in claim 1, further comprising a polarization controller with at least two degrees of freedom connected at an input of said first PMD element,
5   wherein said optical element has no more than two degrees of freedom.

8.   The device as in claim 7, wherein said polarization controller has three degrees of freedom and
10   said optical element has one degree of freedom.

9.   The device as in claim 8, wherein said optical element is an adjustable phase retarder formed of a birefringent material.
15

10.   The device as in claim 9, wherein said phase retarder has adjustable directions of its principal polarization axes.

20   11.   The device as in claim 9, wherein said phase retarder has adjustable indices of refraction along two principal polarization axes.

12. The device as in claim 1, further comprising an optical detector coupled to receive a portion of said optical output optical signal from said second PMD element, and a control unit coupled to said optical

5 detector to produce said control signal in response to a detector signal.

13. A device, comprising:

a first polarization transformer to receive an

10 input optical signal and responsive to a first control signal to rotate a polarization of said input optical signal to produce a first optical signal;

a first polarization-mode dispersion (PMD) element having an input terminal coupled to said first

15 polarization transformer to receive said first optical signal and designed to cause a fixed differential group delay (DGD) in said first optical signal to produce a second optical signal;

a second polarization transformer coupled to

20 said first PMD element to receive said second optical signal and designed to rotate a polarization of said second optical signal to produce a third optical signal under a control of a second control signal; and

a second PMD element coupled to receive said

third optical signal and designed to produce a variable

DGD in said third optical signal in response to a third

control signal to produce an optical output signal.

5

14.   The device as in claim 13, further comprising

an optical detector coupled to receive a portion of said

optical output signal from said second PMD element, and a

control unit coupled to said optical detector to produce

10   said first, said second, and said third control signals

in response to a detector signal.

15.   The device as in claim 14, wherein said control

unit is designed to control said second PMD element to

15   produce a selected and fixed DGD when said detector

signal indicates that a signal quality of said optical

output signal is above a threshold and to produce a

varying DGD when said detector signal indicates that said

signal quality is below said threshold.

20

16.   The device as in claim 13, wherein said second

PMD element includes a nonlinearly-chirped fiber grating

formed of a birefringent fiber material.

17. The device as in claim 13, wherein said second
PMD element includes a first optical path to receive
light of a first principal polarization of said first
optical signal, a second optical path to receive light of

5 a second orthogonal principal polarization of said first
optical signal, and a control portion that varies an
optical delay between said first and said second optical
paths in response to said control signal.

10 18. The device as in claim 13, wherein said second
PMD element includes a plurality of PMD elements
optically connected in series to produce discrete
variable DGD values.

15 19. A method, comprising:
causing a fixed differential group delay (DGD)
in an optical signal to control second-order and higher-
order polarization-mode dispersion (PMD) in said optical
signal to produce a first intermediate signal;

20 causing a rotation of a polarization of said
first intermediate signal to produce a second
intermediate signal; and
causing a second, variable DGD in said second
intermediate signal in response to a control signal to

control the first-order PMD without affecting the second-
order and higher-order PMD.

20. The method as in claim 19, further comprising

5   causing a dynamic control over a polarization of said

optical signal prior to producing said fixed DGD therein

in response to a change in an input polarization of said

optical signal, and wherein said second DGD is controlled

at a fixed value when a signal quality of said optical

10   signal is measured to be above an acceptable level and is

varied at different values when said signal quality is

below said acceptable level.

21. A method for controlling a device that includes

15   a first adjustable polarization transformer that changes

a polarization of an optical signal, a first

polarization-mode dispersion (PMD) element that produces

a fixed differential group delay (DGD) in an optical

signal, a second adjustable polarization transformer, and

20   a second PMD element that produces a varying DGD in an

optical signal, comprising:

causing a signal quality of an optical output

signal that is produced by transmitting through said
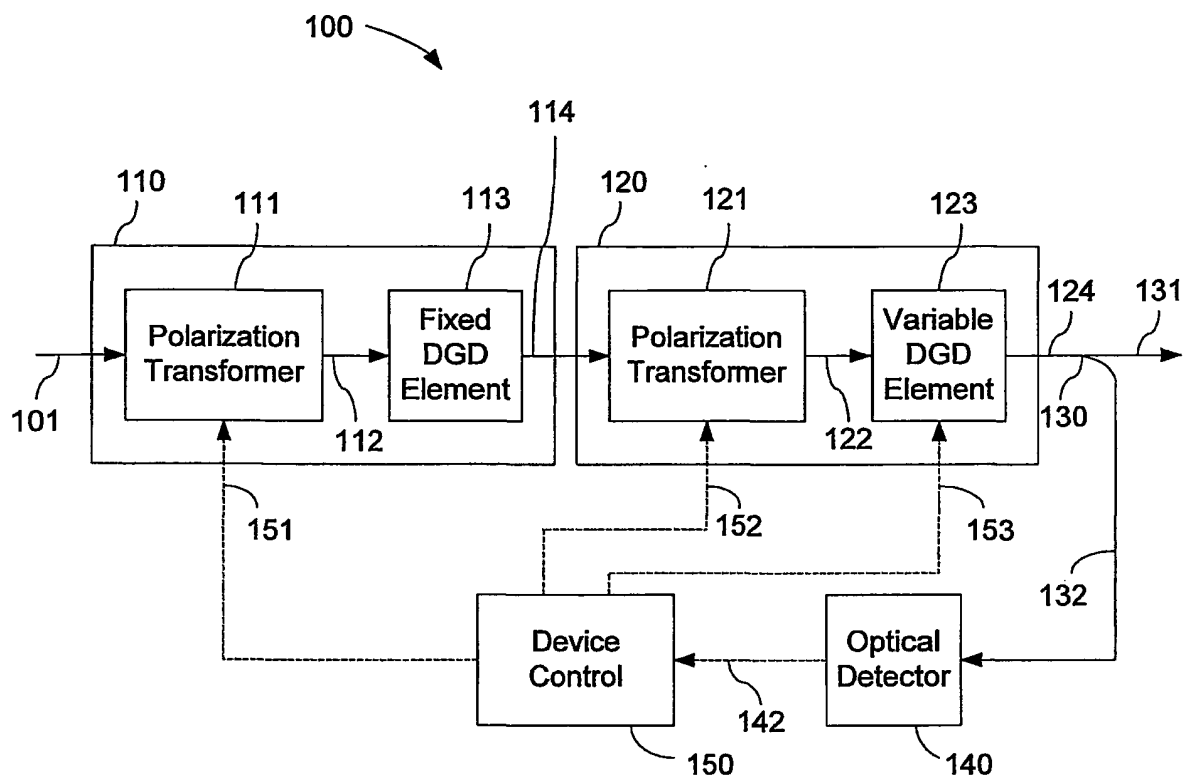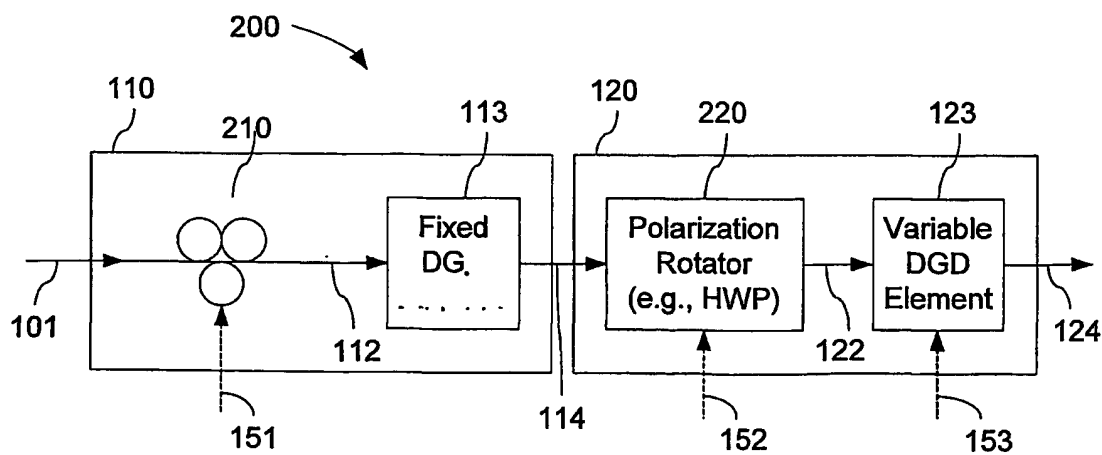
device to be measured;

causing a dynamic adjustment of said first and
said second polarization transformers to change
polarization of light entering said first PMD element and
polarization of light entering said second PMD element,
5   respectively; and

    causing said second PMD element to be
controlled to produce a fixed DGD value when said signal
quality is measured to be above an acceptable level and
to vary at different DGD values when said signal quality
10   is below said acceptable level.

    22.   The method as in claim 21, wherein a bit error
rate of said optical output signal is measured to
determine said signal quality.

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    23.   The method as in claim 21, wherein an opening
of an eye diagram of said optical output is measured to
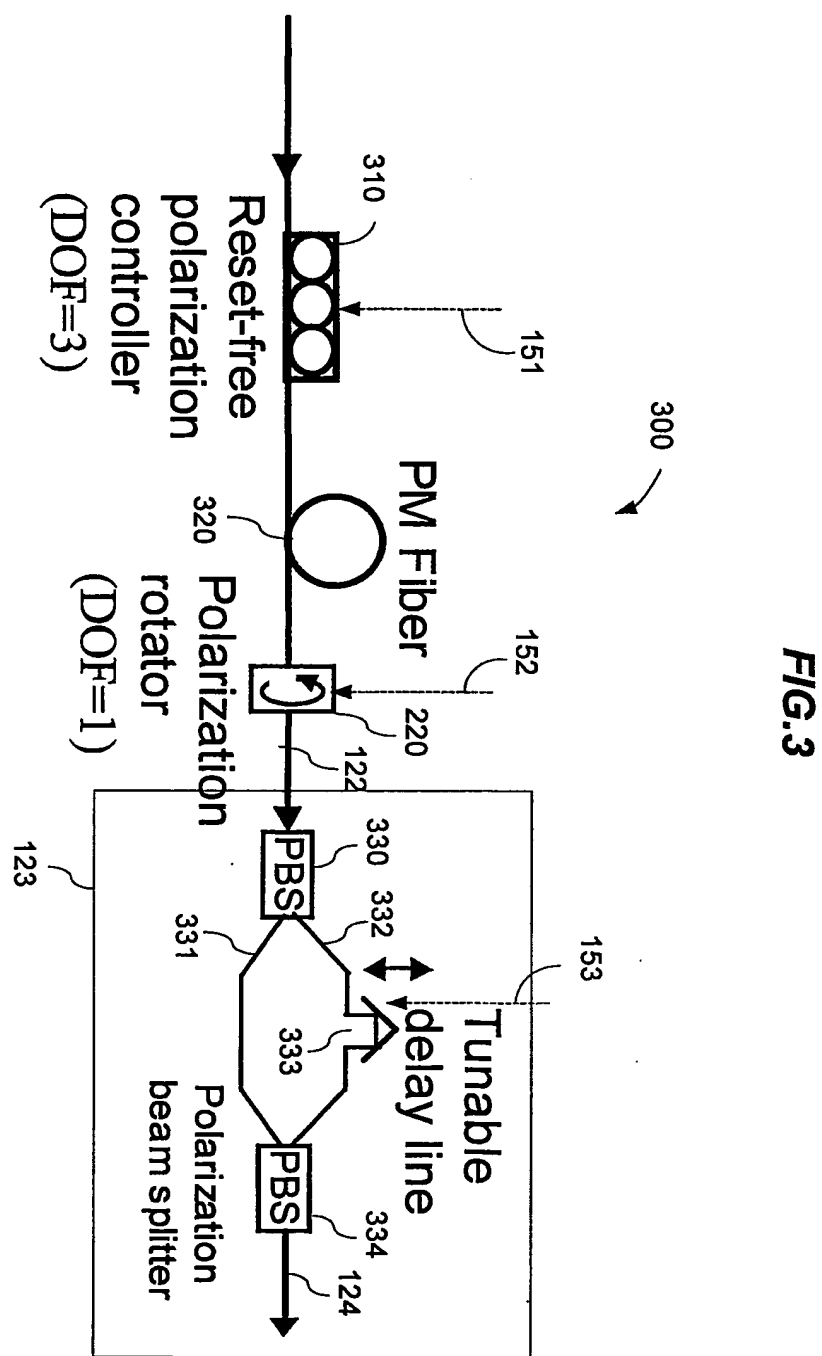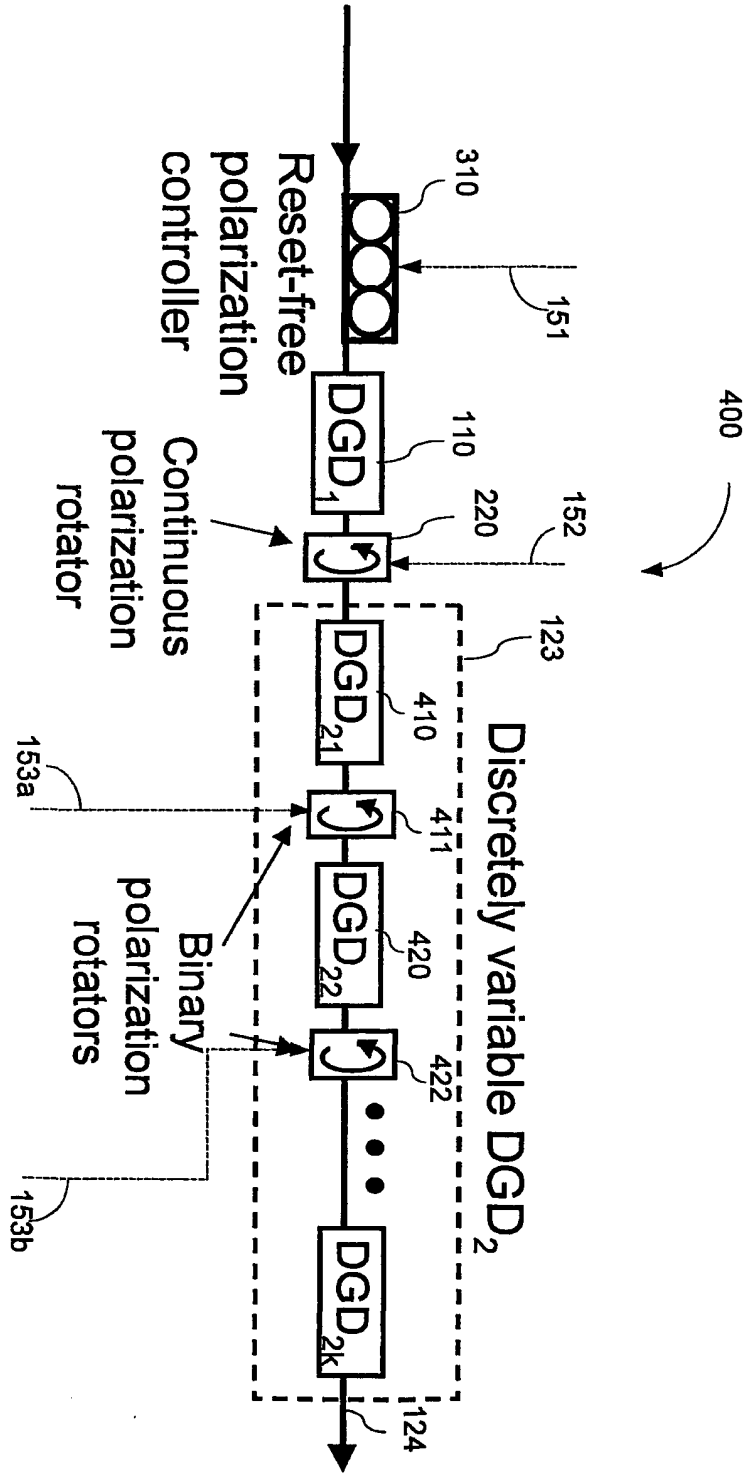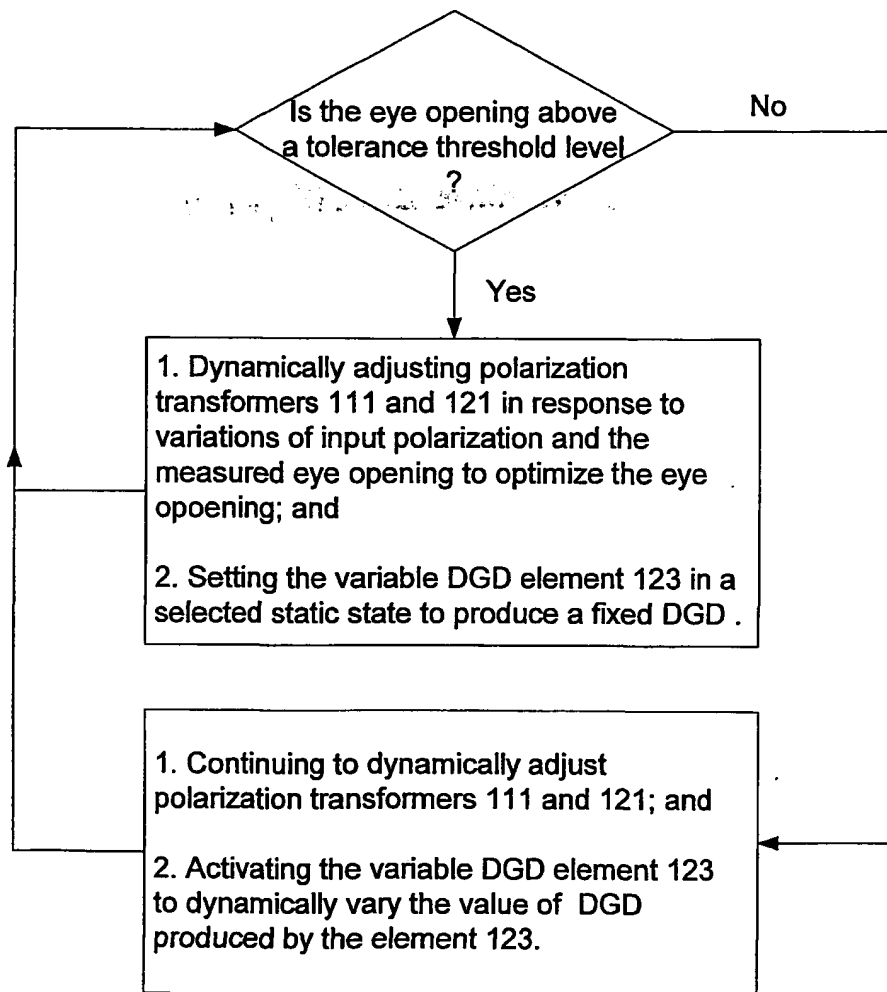determine said signal quality.

FIG. 1

100

FIG. 2

200

FIG.3

FIG. 4

FIG. 5

Is the eye opening above a tolerance threshold level ?

No

Yes

1. Dynamically adjusting polarization transformers 111 and 121 in response to variations of input polarization and the measured eye opening to optimize the eye opoening; and

2. Setting the variable DGD element 123 in a selected static state to produce a fixed DGD .

1. Continuing to dynamically adjust polarization transformers 111 and 121; and

2. Activating the variable DGD element 123 to dynamically vary the value of DGD produced by the element 123.

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